A SURVEY OF RESEARCH PERFORMED AT NASA LANGLEY RESEARCH CENTER'S IMPACT DYNAMICS RESEARCH FACILITY

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Abstract

The Impact Dynamics Research Facility (IDRF) is a 240-ft.-high gantry structure located at NASA Langley Research Center in Hampton, Virginia. The facility was originally built in 1963 as a lunar landing simulator, allowing the Apollo astronauts to practice lunar landings under realistic conditions. The IDRF was designated a National Historic Landmark in 1985 based on its significant contributions to the Apollo Program. In 1972, the facility was converted to a full-scale crash test facility for light aircraft and rotorcraft. Since that time, the IDRF has been used to perform a wide variety of impact tests on full-scale aircraft and structural components in support of the General Aviation (GA) aircraft industry, the US Department of Defense, the rotorcraft industry, and NASA in-house aeronautics and space research programs. The objective of this paper is to describe most of the major full-scale crash test programs that were performed at this unique, world-class facility since 1974. The past research is divided into six sub-topics: the civil GA aircraft test program, transport aircraft test program, military test programs, space test programs, basic research, and crash modeling and simulation.

Introduction

The Impact Dynamics Research Facility was originally built in the early 1960's as the Lunar Landing Research Facility (LLRF) and became operational in 1965. The steel A-frame gantry structure is 240-ft. high, 400-ft. long, and 265-ft. wide at the base. The LLRF was used to train Apollo astronauts to fly in a simulated lunar environment and to practice landing on the lunar surface. The astronauts performed these tests in a Lunar Excursion Module Simulator (LEMS) that was suspended from the gantry. The gantry suspension system was designed to produce an upward force equal to 5/6th of the total weight of the LEMS, thus simulating the reduced lunar gravity. The surface beneath the gantry was modified to resemble the lunar landscape and many of the tests were performed at night to mimic the lighting conditions during the actual landing. A photograph of the LEMS descending onto the simulated lunar surface at the LLRF is shown in Figure 1. In 1985, the facility was designated a National Historic Landmark based on its significant contributions to the Apollo Program. The operational features of the LLRF and the results of flight tests performed using the facility are described in References 1 and 2, respectively.

Figure 1. Photograph of the LEMS descending to the simulated moon surface.

In 1972, the LLRF was converted into an Impact Dynamics Research Facility (IDRF) for investigating the crashworthiness of General Aviation (GA) aircraft and rotorcraft. A unique feature of this facility is the ability to perform crash tests of light aircraft and rotorcraft under free-flight conditions; and, at the same time, to control the impact attitude and velocity of the test article. Another unique feature is the ability to conduct full-scale crash tests over a wide range of combined forward and vertical velocity conditions. Most GA aircraft tests are performed such that the forward component of velocity is higher than the vertical component. For example, the 1994 crash test of the Lear Fan 2100 aircraft was performed at 82-fps forward and 31-fps vertical velocity. Conversely, helicopters are typically tested such that the vertical velocity component is higher than the forward component. For example, the 1999 crash test of the Sikorsky Advanced Composite Airframe Program (ACAP) helicopter was performed at 31.5-fps forward and 38-fps vertical velocity.

The purpose of full-scale crash testing is to obtain experimental data characterizing the dynamic structural response of aircraft and to quantify the loads transmitted to the occupants. These data can be used to validate numerical predictions through test-analysis correlation, or to evaluate crashworthy design concepts for the aircraft structure and seat and restraint systems.[3] Since the first full-scale crash test was performed in February of 1974, the IDRF has been used to conduct 41 full-scale crash tests of GA aircraft including landmark studies to establish baseline crash performance data for metal and composite aircraft, 11 full-scale crash tests of helicopters including crash qualification tests of the Bell and Sikorsky ACAP helicopters, 48 Wire Strike Protection System (WSPS) qualification tests of Army helicopters, 3 vertical drop tests of B707 fuselage sections, 8 vertical drop tests of a crashworthy composite fuselage section, and 50+ drop tests of the F-111 crew escape capsule. In addition, the facility has been used to perform numerous component tests in support of the Mars Sample Return (MSR) Earth Entry Vehicle (EEV) program, as well as a number of other unique experiments. Some of these tests include a tethered-hover test of the XFV-12A, a vertical drop test of a CH47 helicopter fuselage section with a nuclear weapons container, and several drop tests of an energy-absorbing pallet for a remote-controlled vehicle.

The objective of this paper is to describe the IDRF gantry facility and to briefly discuss most of the major full-scale test programs that have been performed at the IDRF since 1974. The past research is divided into six areas: the civil GA aircraft test program, transport aircraft test program, military test programs, space test programs, basic research, and crash modeling and simulation.

Description of the IDRF

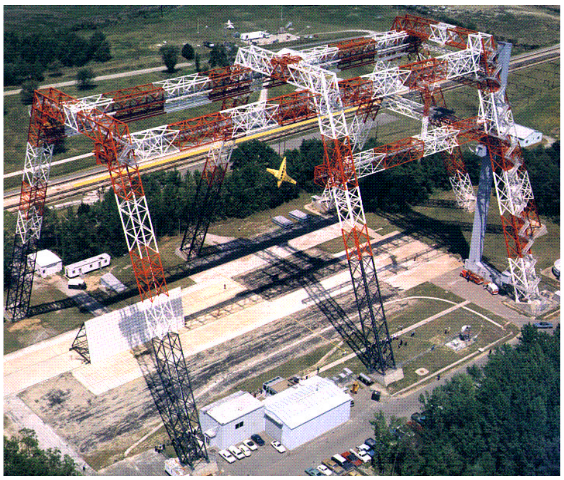
A photograph of the IDRF is shown in Figure 2(a). The gantry structure is composed of truss elements arranged in three sets of inclined legs to give vertical and lateral support. One set of inclined legs located at the east end of the gantry provides longitudinal support. An enclosed elevator and a stairway provide access to the overhead work platforms. A movable bridge spans the gantry at the 216-ft. level and traverses the length of the gantry. In 1981, a 70-ft. vertical drop tower, shown in Figure 2 (b), was added beneath the northwest leg of the gantry for the purpose of conducting vertical drop tests of Boeing 707 fuselage sections in support of the Controlled Impact Demonstration (CID). Since that time, numerous vertical drop tests have been performed using this facility.

Full-scale crash tests are performed at the IDRF using a pendulum swing technique. Two pivot-point platforms are located at the top of the west end of the gantry that support two winches for controlling the length of the swing cables. A pullback platform is located on the underside of the movable bridge that also supports a winch for controlling the pullback cable. The swing and pullback cables connect to the aircraft swing and pullback harnesses, which comprise the aircraft suspension system. The harnesses are designed specifically for the aircraft configuration being tested. The cable lengths of the aircraft swing and pullback harnesses can be adjusted to provide a wide range of roll, pitch, or yaw attitudes at impact. The harness cables are typically mounted to hard points on the airframe. During the test, the aircraft is raised through the pullback cable to the desired drop height. Following a countdown, the pullback cable is pyrotechnically cut, releasing the aircraft to swing towards the impact surface. Just prior to impact, the swing cables are pyrotechnically separated from the aircraft such that it is completely unrestrained during the impact. More detailed descriptions of the IDRF full-scale crash test procedures are provided in References 3 and 4.

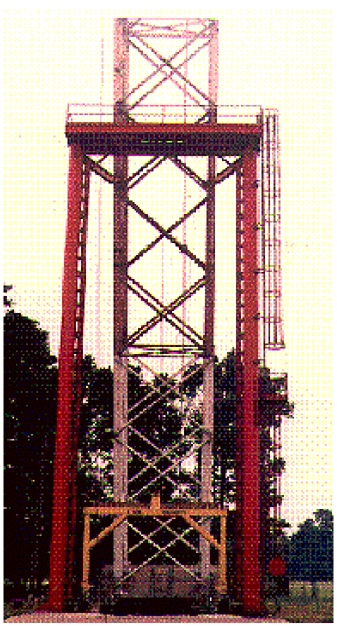
General Aviation Aircraft Test Programs

In 1974, a cooperative research program was initiated between NASA, the FAA, and the GA aircraft industry to improve the crashworthiness of small aircraft.[5-14] The objectives of this program were to determine the dynamic responses of the aircraft structure, seats, and occupants during crash events;

to determine the effect of flight parameters at impact (flight speed, flight-path angle, pitch angle, roll angle, etc.) on the magnitude and pattern of structural damage; to determine the failure modes of the seats and occupant restraint systems; and to determine the impact loads imposed upon the occupants. The program included extensive analytical work, test data evaluation, and structural concept development that were focused on enhancing the survivability of future GA aircraft with minimal increase in weight and cost.



(a) Photograph of the IDRF.



(b) Photograph of the 70-ft. drop tower.

Figure 2. Photographs of the IDRF test facilities.

Dynamic structural response data were obtained by conducting full-scale crash tests of GA aircraft under a variety of impact conditions. In all, 33 crash tests were performed during the 9-year period from 1974 through 1983. Most of the test articles (Piper Navajos, Aztecs and Cherokees) were obtained for scrap aluminum value because the aircraft had been submerged during a flood at the Piper plant in Pennsylvania and they could not be certified, retrofitted or sold. Later crash tests were performed on Cessna 172 aircraft and larger pressurized Piper Navajos. Some of the test parameters included the impact velocity, the attitude of the airframe at impact, and the impact surface (hard surface and soft soil). Photographs of selected impact tests performed in support of the GA aircraft crash test program are shown in Figure 3.

Most of the full-scale crash tests of GA aircraft were performed using the pendulum-swing technique, described previously. This test method was sufficient to achieve impact velocities typical of the take-off and landing velocities of small GA aircraft (81- to 88-fps). However, these impact velocities were insufficient for crash tests of larger pressurized Piper Navajos that were conducted in the early 1980′s. For these tests, a Velocity Augmentation System (VAS) was used in which rockets were attached to the wings of the aircraft. The rockets were fired while the aircraft was in the pullback position, allowing them to build thrust prior to release. Using this procedure, impact velocities of between 132- to 176-fps could be obtained. A photograph of one of the VAS tests of a Piper Navajo is shown in Figure 4.

Since it was not possible to evaluate all potential impact scenarios, most of the tests were performed for impact conditions that represented some of the more serious, but potentially survivable GA airplane crashes. The data obtained during the GA aircraft crash test program was used to define the levels of acceleration typically experienced by the airframe structure and by the occupants during crash events. The occupant data were compared with different human injury prediction criteria to determine injury risk levels during airplane crashes. The structural data from this landmark crash test program was used to establish impact criteria for aircraft seats that are still used as the FAA standard for seat certification testing today. Later, the data were used as the foundation for the Crash Survival Design Guide for GA aircraft.[15]

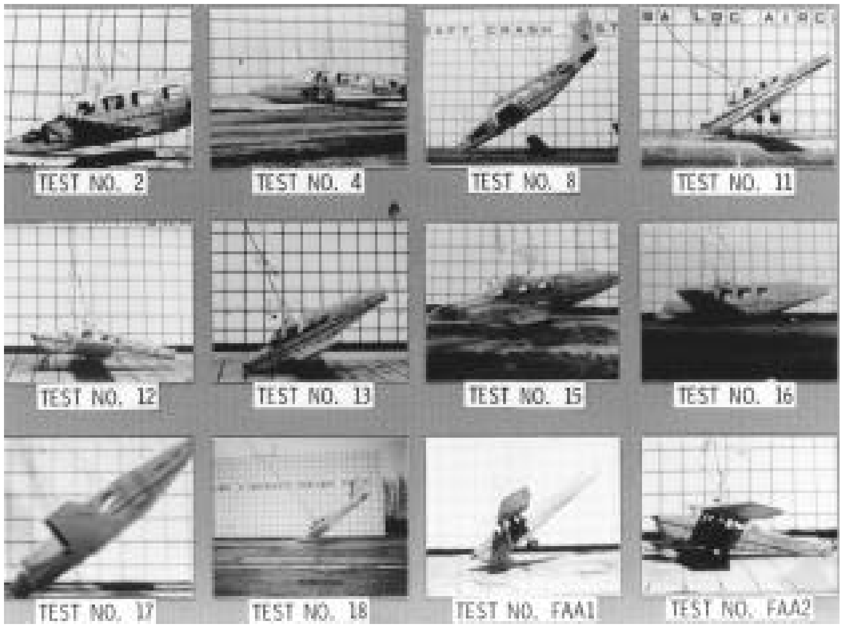


Figure 3. Photographs of several GA aircraft full-scale crash tests performed at the IDRF.

Figure 4. Photograph of a full-scale crash test of a Piper Navajo aircraft with VAS.

Lear Fan 2100 Full-Scale Crash Test

In the early 1980's the focus of the GA crash research program at NASA Langley shifted from metal airframe structures to composite materials. As part of this effort, two prototype Lear Fan 2100 aircraft were obtained for crash testing when the Lear Fan Company went into bankruptcy. The Lear Fan aircraft is constructed primarily of graphite-epoxy composite fabric using a frame-stiffened skin design.[16] The subfloor of the aircraft consisted of stiff aluminum keel beams supported by composite stanchions. Since the airframe did not contain sufficient energy absorbing components, a decision was made to test one aircraft in the unmodified, or baseline, configuration and to retrofit the second aircraft with a composite energy absorbing subfloor. The development of the composite subfloor is described in References 17 and 18. Photographs of the crash test of the baseline Lear Fan aircraft are shown in Figure 5.

(a) Photograph of the aircraft in the release position.

(b) Post-test photograph.

Figure 5. Lear Fan 2100 aircraft crash test.

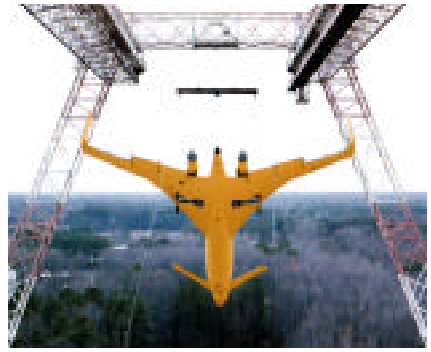
The crash test of the baseline aircraft was performed in 1994 at 82-fps forward and 31-fps vertical velocity conditions onto a rigid impact surface. The aircraft was tested with three load limiting and four standard non-crashworthy aircraft seats, all of which were forward facing. In addition, a plywood bulkhead wall was installed in front of the most rearward pair of seats to accommodate the installation of an airbag. An instrumented anthropomorphic test dummy was restrained in each seat. Results from this crash test showed, for the first time, that floor-level accelerations of this composite aircraft were much higher than those of comparable all-metallic aircraft. These findings indicated that this type of composite airframe design is not optimum for crashworthiness.[19]

Beech Starship

As part of the Advanced General Aviation Transport Experiment (AGATE) research program, a full-scale crash test of the Beech Starship was performed in 1995. The Starship was the first composite aircraft to obtain FAA certification; however, it is no longer in production. The airframe is fabricated of a composite sandwich construction with Kevlar face sheets and a Nomex honeycomb core. The aircraft has built-in crashworthy design features, as described in Reference 20. The full-scale crash test was performed at 83-fps forward and 27-fps vertical velocity at the IDRF. During slide out following the initial impact, a secondary impact occurred onto an earthen barrier. This impact was planned to generate longitudinal loading of the seats and occupants to evaluate an airbag protection system. Pre-release and post-test photographs of the Beech Starship are shown in Figure 6.

Modified Cirrus SR-20

In 1995, NASA awarded a Small Business Innovative Research (SBIR) contract to Terry Engineering, Inc. to investigate design modifications for improved crashworthiness of light aircraft, including anti-plowing features. One objective of the research project was to evaluate aircraft modifications that would alleviate high longitudinal accelerations during soft soil impact. Ideally, the modifications to the aircraft should enable it to skid along the surface of the soil just as it would during an impact with concrete. As part of the SBIR, Terry Engineering worked with Cirrus Aircraft to develop the design modifications. Over a two-year period from 1996-1997 four full-scale crash tests were conducted, two onto concrete and two onto soft soil. Each test was performed for the same impact attitude and velocity conditions. A photograph of one of the four aircraft is shown in Figure 7 in the release position at the IDRF. The modifications were effective and demonstrated the potential of relatively minor design changes to improve overall crash performance of the airframe.[21, 22]



(a) Pre-release photograph.

(b) Post-test photograph.

Figure 6. Pre- and post test photographs of the Beech Starship.

Figure 7. Photograph of the modified Cirrus aircraft.

Modified Lear Fan 2100 Crash Test

A full-scale crash test of a second Lear Fan aircraft was performed at the IDRF in 1999. This aircraft was retrofitted with a composite energy absorbing subfloor and was tested under the same impact conditions as the baseline aircraft, 82-fps forward and 31-fps vertical velocity. The purpose of the test was to evaluate the effectiveness of the new subfloor design, to generate data for correlation with analytical predictions, and to determine the dynamic response of side-facing seats. The aircraft was configured with side-facing seats that were occupied with anthropomorphic test dummies. The main part of the crash test was performed in a similar manner as the 1994 test, with one exception. During slide out of the aircraft following the initial impact, the aircraft hit a plywood and earthen barrier, as shown in Figure 8. The purpose of this secondary impact was to introduce significant longitudinal loads into the airframe to test the ability of the side-facing seats to adequately restraint the occupants. The tests provided data to guide needed improvements in the design of side-facing seats. A dynamic finite element crash simulation was performed of the second Lear Fan 2100 aircraft crash test and analytical predictions were correlated with test data.[23]

Figure 8. Post-test photograph.

Modified Lancair Crash Test

As a final demonstration of the technology developments of the AGATE research program, a full-scale crash test of a modified Lancair aircraft was performed at the IDRF in 2001. The purpose of the test was to demonstrate the efficacy of employing a systems approach to crashworthiness for GA aircraft. Some of the crashworthy features of the aircraft included an energy absorbing subfloor, load-limiting seats, advanced restraint systems, and anti-plowing features. The crash test was performed at 96-fps resultant velocity. This impact condition is much more severe than the current FAA requirements for dynamically certified seats. A photograph of the aircraft just following initial impact is shown in Figure 9. The full-scale crash test of the modified Lancair was successful since the survivable cabin volume was retained during the impact and the occupant loads were within survivable limits.[24]

Figure 9. Photograph of the modified Lancair aircraft immediately after impact.

Transport Aircraft Crash Test Program

In the early 1980's, NASA partnered with the FAA to conduct the Controlled Impact Demonstration (CID) research program.[25-27] The primary objective of the CID was to evaluate the performance of a fuel additive, anti-misting kerosene or AMK, to reduce the potential of a massive fire upon impact of transport jets. As a final demonstration of the AMK technology, a full-scale crash test of a remotely piloted B720 transport jet was conducted in December 1984 at Edwards Air Force Base. A photograph of this test is shown in Figure 10. NASA's interest in the test was in obtaining structural response data during a full-scale crash test of a transport aircraft. IDRF personnel designed the instrumentation layout and developed a redundant data acquisition system to ensure data collection, even in the event of fire. Also, all onboard cameras were thermally protected.

As shown in Figure 10, the B720 transport aircraft impacted the dry lakebed surface in a rolled (left-wing down) and yawed attitude at 17-fps vertical and 248-fps forward velocity. Tank traps, that were positioned to shear the wings, actually cut through an engine, providing a powerful ignition source for post-crash fire. However, in spite of the fire, data were retrieved from 97% of the 350 transducers on the aircraft. This data provided the first quantitative measurements of transport jet structural response during an actual free-flight crash. In addition to planning and coordinating the structural response data for the crash test, IDRF personnel were also heavily involved in performing crash simulations of the CID test. Excellent correlation was obtained for these simulations, thus validating the modeling approach and demonstrating a useful prediction tool for crash assessment.[26]

In preparation for the CID crash test, vertical drop tests of three B707 transport fuselage sections were performed using the 70-ft. drop tower at the IDRF.[28-30] The objectives of the tests were to evaluate the integrity of the data acquisition systems that would be used on the CID and to generate data for model validation. The three sections were from the forward, center (wing box), and aft compartments of the aircraft. The drop tests were performed at 20-fps vertical velocity, which was slightly higher than the planned vertical impact condition for the CID. A post-test photograph of the B707 forward fuselage section is shown in Figure 11. In addition, dynamic finite element models were developed and executed. The analytical and experimental correlations performed for these drop tests and the CID represented the first validated crash simulations of transport aircraft structures.

Figure 10. Photograph of the CID full-scale crash test of a B720 transport aircraft.

Figure 11. Post-test photograph of the B707 forward fuselage section vertical drop test.

Military Crash Test Programs

<u>CH-47 Helicopter</u>
In 1975 and 1976, two full-scale crash tests of the CH-47 "Chinook" helicopter were performed in support of the US Army Aviation Applied Technology Directorate (AATD) located at Ft. Eustis, VA. The objectives of the tests were to evaluate the load-limiting performance of the seats, the structural response of the airframe, and the integrity of the cargo restraint systems.[31,32] The CH-47 helicopter is heavy lift, troop and equipment transport helicopter. A pre-test photograph of the CH-47 helicopter is shown in Figure 12.

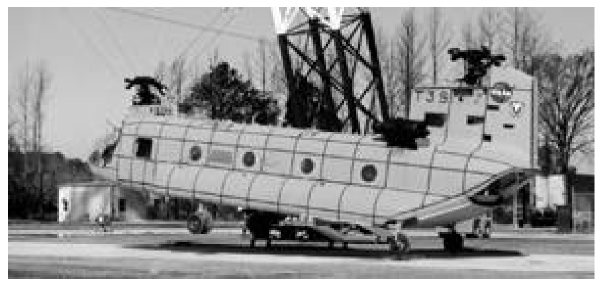


Figure 12. Photograph of a CH-47 helicopter.

<u>Tethered-Hover Test of the XFV-12A</u>
In early 1978, tethered-hover tests of the full-scale XFV-12A were performed at the IDRF in support of Rockwell and the US Navy. A photograph of the XFV-12A test is shown in Figure 13. The IDRF was modified extensively to permit static and dynamic tethered-hover tests of this powered V/STOL aircraft. During six months of testing of the XFV-12A it became apparent that major deficiencies existed in hovering flight, including insufficient lift due to marginal thrust augmentation. The NASA tests helped influence the Navy's decision to cancel the XFV-12A program.[33, 34]

Figure 13. Tethered-hover test of the XFV-12A.

Wire Strike Protection System

In 1979, the US Army AATD sponsored a series of Wire Strike Protection System (WSPS) qualification tests on 8 different Army helicopters.[35, 36] Based on helicopter accident data, it was found that many accidents occurred during nap-of-the-earth flight when pilots accidentally flew the helicopters into utility cables. A passive system was designed to alleviate this problem. Blade-type devices are attached to the top and bottom of the helicopter fuselage. When encountered, the cables are intended to slide either up or down the front of the helicopter and get caught in the blade devise. The cable is then notched and severed. Qualification tests were performed at the IDRF to validate the WSPS design for eight different Army helicopters. The tests were performed by suspending a 3/8-in.-diameter steel cable from two telephone poles located on opposite sides of the gantry. The helicopter was suspended from the gantry, pulled back into the release position, and then released to swing into the cable. A photograph showing a WSPS test of an AH-1 Cobra helicopter is shown in Figure 14. The WSPS concept, as validated during tests at the IDRF, has been highly effective in protecting helicopters against mishaps caused by wire strikes. Fewer accidents, injuries, and fatalities have resulted in Army helicopters that are equipped with WSPS. Currently these systems are installed fleet-wide on both military and commercial helicopters.

Figure 14. Photograph of a WSPS test performed on an AH-1 Cobra helicopter.

Full-Scale Crash Test of the YAH-63

In July 1981, a full-scale crash test of the YAH-63 prototype helicopter was conducted at the IDRF.[37] This helicopter was designed and manufactured by Bell Helicopter Textron as its bid in the competition for the Army's advanced attack helicopter. The crash test was performed to evaluate the energy-absorbing and load-limiting features of the airframe and landing gear. This test was the first crash test of a helicopter with built-in crashworthy design features, that was manufactured before publication of the Army's crash design standard, MIL-STD-1290 (AV).[38] A photograph of the YAH-63 during the crash test is shown in Figure 15. The Bell airframe did not win the award, which went to the Hughes Helicopter (now Boeing) AH-64 Apache.

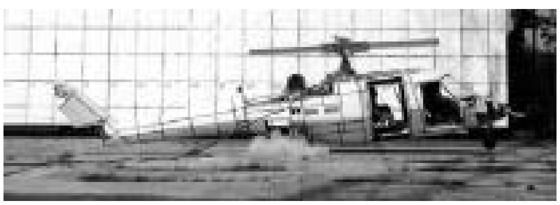
Figure 15. Photograph of the full-scale crash test of the Bell YAH-63 helicopter.

ACAP Crash Qualification Tests

Full-scale crash qualification tests were performed at the IDRF on the Bell and Sikorsky Advanced Composite Airframe Program (ACAP) helicopters in 1987.[39-41] The purpose of the Army-sponsored ACAP was to demonstrate the potential of advanced composite materials to save weight and cost in airframe structures while achieving systems compatibility and meeting military requirements for vulnerability reduction, reliability, maintainability, and survivability. In 1981, the US Army awarded separate contracts to Bell Helicopter Textron and Sikorsky Aircraft Company to develop, manufacture, and test helicopters constructed primarily of advanced composite materials. Each company manufactured three airframes that were tested under a variety of static and dynamic conditions to demonstrate compliance with the program objectives. In addition, one helicopter airframe from each company was equipped to become a flying prototype. Crash tests of the Bell and Sikorsky ACAP static test articles were conducted in 1987 at the IDRF in support of the US Army AATD to demonstrate their impact performance and to verify compliance with crash requirements. Pre- and post-test photographs of the full-scale crash tests are shown in Figure 16. The Bell ACAP helicopter was impacted with combined 42-fps vertical and 27-fps forward velocity, while the Sikorsky ACAP helicopter was impacted at 39-fps vertical velocity. These tests demonstrated the successful application of composite materials to save weight and maintenance costs in rotorcraft design, while achieving improved crash performance.

(a) Pre-test photograph of the Bell and Sikorsky ACAP helicopters.

(b) Bell ACAP helicopter during crash test.



(c) Sikorsky ACAP helicopter during crash test.

Figure 16. Pre- and post-test photographs of the Bell and Sikorsky ACAP helicopter crash tests.

Active Crew Restraint Systems Testing

In the early 1990′s the US Army was actively supporting the development of crew restraint technologies as a result of studies that showed that a high percentage of injuries in crashes occurred as a result of occupants striking interior cockpit structures. In 1993, two full-scale crash tests of an AH-1S Cobra helicopter were conducted at the IDRF to demonstrate, under realistic crash conditions, the performance of active crew restraint systems. In particular, the tests, sponsored by the US Army AATD, were performed to evaluate the Inflatable Body and Head Restraint System (IBAHRS) and the Cockpit Air Bag System (CABS).[42] IBAHRS is an active restraint system that consists of two sealed air bags integrated into a standard five-point restraint harness, with gas generators, a crash sensor, and airframe specific modifications. The airbags are attached to the underside of the straps to restrain the torso of the occupant. CABS is an airframe-mounted system similar to that used by the automotive industry. The bag design is cockpit specific and the sensor is tuned to the specific airframe crash characteristics. The combined forward and vertical velocity conditions that were selected for both tests are considered moderately severe and represent a high percentage of survivable mishaps. The impact tests occurred on soft soil, instead of concrete. A photograph is shown in Figure 17 of a full-scale crash test of the AH-1S helicopter with IBAHRS and CABS deployed. In both tests the IBAHRS and CABS were fully deployed at the proper time to provide their maximum protection capabilities. This program demonstrated that these systems have the potential to reduce the number of injuries and fatalities resulting from contact with interior cockpit structures in a crash. Currently, the US Army has ordered retrofit of UH-60 Black Hawk and OH-58 Kiowa Warrior helicopters to be outfitted with CABS based on the results of this successful test program.

Figure 17. Photograph of a crash test of the AH-1S helicopter with crew restraint systems.

Evaluation of an External Fuel System

In 1994, three UH-1 Huey helicopters were crash tested at the IDRF to qualify an External Fuel System (EFS) proposed for National Guard helicopters. The external fuel system included left and right conformal tanks each with a capacity of approximately 75 gallons that attach to hard points on the fuselage subfloor sides. The three impact tests were conducted with a nominal 9,000 lb. gross weight for the helicopters including the EFS, simulated fuel, attached swing fixture, and instrumentation. The tests were conducted by swinging the aircraft pendulum-style into the ground with combined impact velocities from 32- to 51-fps. All tests were conducted with a 10-degree nose-up pitch and 0-degree yaw attitude. In addition, the helicopters were rolled 15-degree to the left for the first two tests and 26-degree to the right for the third test. The pass/fail criteria for these tests were based on the nature and amount of water leakage from the tanks. Because of the higher specific gravity of water compared to aviation fuel, the main and external fuel tanks were only filled to 80% of their capacity to represent the weight of the aviation fuel. Red and green water soluble dyes were used in the EFS tanks to identify the source of any leakage that might occur and to distinguish leakage in the EFS from leakage in the main fuel system where clear water was used. A pre-test photograph of the UH-1 helicopter outfitted with external fuel tanks is shown in Figure 18. The successful qualification of the EFS has resulted in increased range for these National Guard helicopters.

Figure 18. Pre-test photographs of the UH-1 Huey helicopter with external fuel tank.

F-111 Crew Escape Module

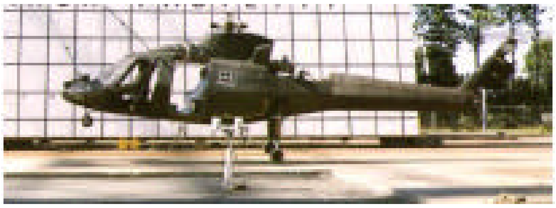
In the event of an emergency, the F-111 crew escape module is separated from the aircraft and the module descends to Earth with the aid of a parachute system. However, even with the parachute system, the Air Force reported that the impact of the crew module with the ground produced a high percentage of injuries and some fatalities. Consequently, an air bag energy dissipation system was designed for the crew escape module. The air bag was located on the flat, underside of the module and contained blow out plugs that were designed to tailor the amount of energy absorbed. Beginning in the 1980's and continuing through the mid-1990's, impact tests of the F-111 crew escape module were performed at the IDRF in support of the U.S. Air Force. During the 15-year period of time, over 60 to 70 impact tests were performed of the F-111 crew module with different air bag designs. Many of the tests were conducted onto a soft soil surface under a variety of roll, pitch, and yaw angles to represent the range of impact attitudes possible with a parachute landing.[34] A photograph of one of these tests is shown in Figure 19.

Figure 19. Photograph of the F-111 crew escape module with airbag attenuation system.

Sikorsky ACAP Flight Test Article

A full-scale crash test of the Sikorsky ACAP helicopter (flight test article) was performed at the IDRF in 1999. The purpose of the test was to obtain experimental data for validation of a finite element crash simulation. The helicopter was the flight test article built by Sikorsky Aircraft under sponsorship by the U.S. Army during the ACAP. The helicopter is constructed primarily of advanced composite materials and was designed to meet the Army's stringent MIL-STD-1290 (AV) crashworthiness criteria.[38] For the crash test, the aircraft was outfitted with two crew and two troop seats and four instrumented anthropomorphic dummies. The test was performed at 38-fps vertical and 32.5-fps forward velocity onto a rigid impact surface.[43] Approximately 120 channels of dynamic data were collected. Photographs of the helicopter taken just prior to impact and post-test are shown in Figure 20.

In addition to obtaining structural impact data for validating the computer simulation, several ancillary experiments were included. A programmable electronic crash sensor unit (ECSU) was mounted on the cabin floor near the troop seats. The sensor was typical of the kind that might be used to fire an airbag. During the impact test, the ECSU was wired to turn on a light as an initiation indicator. This experiment showed that the crew station was not a good location for an ECSU that uses a change in filtered acceleration to initiate firing of an airbag.



(a) Photograph of the Sikorsky ACAP helicopter at impact.

(b) Post-test photograph.

Figure 20. Pre- and post-test photographs of the Sikorsky ACAP helicopter.

During the crash test of the Sikorsky ACAP helicopter, the pilot and copilot dummies were seated in two military-qualified load-limiting seats from two different vendors. The troop dummies were seated in ceiling-suspended troop seats, each with two wire-bender energy absorbers that were mounted in the rear cabin area of the helicopter. The detailed seat and occupant response data obtained from the crash test were evaluated and the occupant data were correlated with several different criteria to determine the risk of injury for this crash test.[44] The overall assessment of occupant injury indicates that the ACAP helicopter crash test resulted in a moderate to high level of risk for injury. Although some injuries would likely have occurred in this crash, the probability of a fatality is considered small.

UH-60 Helicopter with External Fuel Tanks

The US Army has retrofitted its entire helicopter fleet with crashworthy internal fuel systems to greatly reduce post-crash fire hazards. It also has a large inventory of 230-gallon external fuel tanks that were originally designed for ferry missions only and which could be jettisoned. These external fuel tanks were not designed to the same crash resistance standard as the internal fuel tanks. Because of the increased use of these tanks in low-level flying missions where the tanks cannot be safely jettisoned during a mishap, the external tanks need to be as crash resistant as the on-board tanks.

In December of 1999, a UH-60 Black Hawk helicopter was crash tested at the IDRF to verify the performance of two modified 230-gallon external fuel tanks.[45] The external fuel tanks were attached to the left and right outboard positions on the helicopter using the external stores support wings. The tanks were filled approximately 80% full of water to simulate the full-tank weight of JP-8 fuel. The helicopter was impacted with vertical and forward velocities of 42- and 50-fps, respectively onto concrete with an attitude of 6-degrees nose-up pitch, 17-degrees left roll, and 17-degrees right yaw. These impact conditions are much more severe than those specified in MIL-STD-1290 (AV) for occupant survivability.[38] A photograph depicting the full-scale crash test of the UH-60 Black Hawk helicopter is shown in Figure 21. The results of the test indicate that both external fuel tanks survived the severe impact condition with only minor leakage, even though they experienced a large transient pulse during the impact test. These findings validated the crash resistance of the modified fuel tank design allowing the Army to more fully utilize these tanks to provide extended range for helicopter missions.

Figure 21. Photographs of the UH-60 Black Hawk helicopter full-scale crash test.

Space Test Programs

Mars Sample Return Earth Entry Vehicle
In 1997 NASA Langley Research Center performed a technology development program for the final phase of a Mars sample retrieval and Earth return mission. The final phase of the mission required the return of rock and soil samples from Mars using a passive Earth-entry, descent, and landing capsule.[46] A unique feature of the Earth Entry Vehicle (EEV) was a crushable energy absorbing cellular sphere that was required to cushion the sample container during earth impact at terminal velocity (without a parachute) and assure sample containment. Design, analysis, and testing of the EEV energy absorber were conducted at the IDRF. Preliminary tests of the structure were accomplished through simple free-fall drops from the 240-ft. tall gantry structure. Subsequent tests were performed with the aid of a custom bungee accelerator with the capability of catapulting spherical containment vessels to speeds of up to 164-fps (over 100-mph). Moreover, the unique test facility offered a wide choice of impact surfaces and impact attitudes. A photograph of the bungee accelerator and cellular sphere energy absorber are shown in Figure 22. A complete description of the design, fabrication, and testing program for the EEV energy absorber can be found in Reference 47 and details of the dynamic finite element analysis of the cellular sphere are documented in Reference 48.

Mars Sample Return Scaled Parachute Tests
In October 2001, a research project was initiated to evaluate methods of imparting a predetermined deceleration profile on a scaled parachute system to simulate the effect of thruster firing and the subsequent off-loading response of the parachute. After successful preliminary evaluation of several methods, the rip-stitch method was selected and used in subsequent tests of the scaled system that included a dynamically scaled parachute and a scaled payload mass. A photograph of the test assembly shortly after release is shown in Figure 23.

Basic Research Programs

The previous sections of this paper described test programs that were performed at the IDRF in support of both customer-funded and in-house projects. Additional research has been performed on more fundamental problems related to crash safety. This research has been performed since the early 1970's and continues to the present time. A few of the past and ongoing research projects will be highlighted.

(a) Bungee accelerator test.

(b) Post-test photograph of the cellular sphere.

Figure 22. Photographs of the Mars sample return test program.

Energy Absorbing Subfloor Concepts
At various stages during the crash dynamics research program, work has been performed to evaluate both metal and composite energy absorbing subfloor concepts. In GA aircraft and rotorcraft, the subfloor consists of keel beams and fuselage frames. The region where the keel beams and the fuselage frames intersect is typically very stiff. In a crash, the dynamic loads are transmitted through this "hard point" to the floor and occupants. Consequently, several research projects have been conducted to evaluate both metal and composite energy absorbing cruciform designs, representing the keel beam and fuselage frame intersection, for application to GA aircraft and rotorcraft. This work is described in References 17, 18, 49, and 50. The cruciform designs were tested under quasi-static and dynamic loading conditions and finite element models were developed to predict the structural response.

Figure 23. Scaled parachute assembly test.

Composite Fuselage Frame Development
Another long-term research project has focused on the development of an energy absorbing composite fuselage frame for transport aircraft. Typically, transport aircraft are manufactured with a frame and stringer skeletal structure covered by an outer skin. The aircraft are constructed of aluminum. In a crash, the aircraft structure below the floor typically deforms plastically absorbing a great deal of energy. However, structural composite materials generally fail in a brittle fashion, exhibiting very little plastic deformation. Consequently, this research project has been focused on development of a composite fuselage frame that will fail progressively in a plastic-like mode during a crash. In addition to specimen design and testing, finite element models have been developed and analytical predictions have been correlated with fuselage frame impact response.[51-53]

Test Method for Seat Cushion Materials
In 1999, a research project was initiated to develop a database of foam material properties for seat cushion design. The cushion in an aircraft seat is the last component available for occupant protection in a crash. However, no database of material properties currently exists to allow designers to tailor the load-limiting capabilities of their seat cushion designs. The focus of this research project is to develop a dynamic test method for generating foam cushion response data and to perform some baseline tests on common seat cushion materials to initiate development of the database.[54]

Crash Modeling and Simulation

An important aspect of crashworthiness research is the demonstration and validation of analytical/computational tools for accurate simulation of airframe structural response to crash loads. The "validation of numerical simulations" was identified as one of five key technology shortfalls during the Workshop on Computational Methods for Crashworthiness that was held at NASA Langley Research Center in 1992.[55] Analytical codes have the potential to greatly speed up the crashworthy design process, to help certify seats and aircraft to dynamic crash loads, to predict seat and occupant response to impact with the probability of injury, and to evaluate numerous crash scenarios not economically feasible with full-scale crash testing.

NASA became involved in analysis methods for crash simulation in the late 1970's when it co-sponsored with the FAA and Grumman the initial development of Dynamic Crash Analysis of Structures (DYCAST). DYCAST is a nonlinear, transient dynamic finite element code developed by Grumman Aerospace Corporation for crash simulation of aircraft structures.[56] IDRF and Boeing personnel used DYCAST to simulate the vertical drop tests of the B707 fuselage sections, as well as the full-scale crash test of the B720 transport aircraft. In the early 1990's, IDRF personnel began using the public-domain DYNA3D and NIKE3D codes that were developed by Lawrence Livermore National Laboratories under Department of Energy sponsorship.[57, 58] These finite element codes were developed to analyze high-speed structural impact problems using explicit (DYNA3D) and implicit (NIKE3D) time integration. The public-domain version of DYNA3D has since been obtained by several vendors, modified, and marketed as commercial codes including LS-DYNA, PAM-CRASH, and MSC.Dytran.[59-61] Since 1997, a team of IDRF personnel have been actively involved in validating numerical simulations using the current generation of crash analysis codes. In the past several years, the IDRF team has performed numerous customer-funded and in-house research projects involving crash simulations. A few of these projects will be highlighted in this section of the paper.

Sikorsky ACAP Helicopter Crash Test
In 1998, a research project was initiated to demonstrate the capabilities of state-of-the-art commercial crash simulation codes in predicting the dynamic

structural response of a prototype composite helicopter, the Sikorsky ACAP helicopter, during a full-scale crash test. A crash simulation of the full-scale drop test was developed using the commercial nonlinear, explicit transient dynamic code, MSC.Dytran.[61] The objective of the crash simulation was to evaluate the capabilities of the code in predicting the response of a composite airframe subjected to impact loading. An existing NASTRAN modal-vibration model of the Sikorsky ACAP helicopter was modified and converted into a model suitable for crash simulation.[62] The MSC.Dytran model is shown in Figure 24. A two-stage modeling approach was implemented for the crash simulation and an external user-defined subroutine was developed to represent the complex landing gear response. Analytical predictions of structural deformation and failure, the time sequence of events, and the dynamic response of the airframe structure were generated. The numerical results were correlated with the experimental data to validate the simulation.[63-65] The level of agreement obtained between the experimental and analytical data builds further confidence in the use of nonlinear, explicit transient dynamic finite element codes as a crashworthy design and certification tool for aircraft.

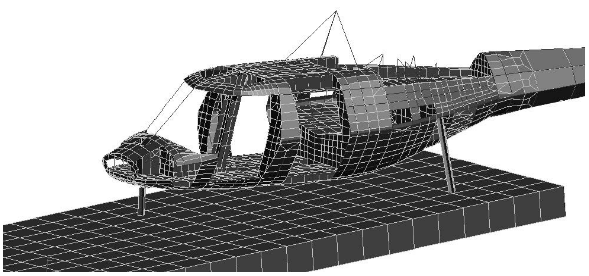
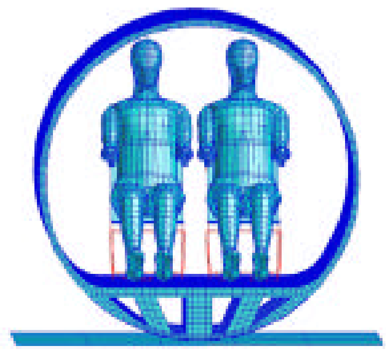


Figure 24. MSC.Dytran model of the Sikorsky ACAP helicopter.

Drop Test of a Composite Fuselage Section

In April 2001, a vertical drop test was performed of a crashworthy composite fuselage section.[66-69] The purpose of the test was to evaluate the crashworthy performance of the fuselage section under a more realistic loading environment with seats and dummies and to provide data for correlation with an integrated structural and human occupant crash simulation. The fuselage section and seats were modeled using MSC.Dytran and the anthropomorphic dummies were modeled using a human occupant simulation code, Articulated Total Body (ATB).[70] The integrated fuselage section and ATB model is shown in Figure 25 along with a post-test photograph of the fuselage section. The integrated simulation accurately predicted the structural response of the fuselage section, the deformation of the seats, and the human occupant responses that were correlated with test data from the test dummies.



(a) Fuselage section model.

(b). Post-test photograph.

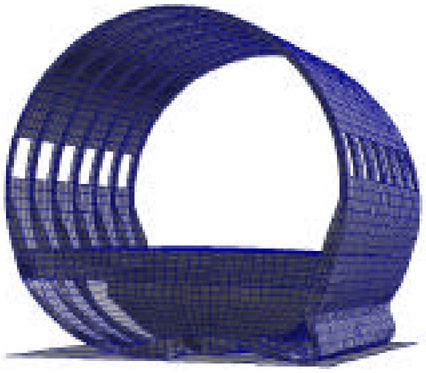
Figure 25. Integrated structural and human occupant model of the composite fuselage section.

Recently, the composite fuselage section has been used as a test bed to evaluate the influence of impact surface on structural response. Three drop tests of the fuselage section have been performed, one onto a rigid (concrete) surface, one onto soft soil (sand), and the other onto water. Crash simulations of each of these drop tests have been and are being performed, including a coupled Eulerian-Lagrangian simulation of the water impact problem.[71, 72] This project is supported by a cooperative research agreement with Bell Helicopter Textron and the National Rotorcraft Technology Center Rotorcraft Industry Technology Association (NRTC/RITA).

Two Drop Tests of B737 Fuselage Sections

In 1998, an Inter Agency Agreement was signed between ARL-VTD and the FAA Technical Center to perform full-scale crash simulations of two vertical drop tests of B737 fuselage sections. The first drop test was conducted in 1999 of a 10-ft. long B737 fuselage section with a water-filled conformable auxiliary fuel tank mounted beneath the floor. The test was performed at the Dynamic Drop Test Facility located at the FAA Technical Center in Atlantic City, NJ. A finite element model of the fuselage section was developed from hand measurements, since no engineering drawings were available. The simulation accurately predicted the time sequence of events, structural deformation, and the floor-level acceleration responses.[73, 74] A post-test photograph of the B737 fuselage section with auxiliary fuel tank and a picture of the deformed model are shown in Figure 26.

(a) Post-test photo of the B737 fuselage section.

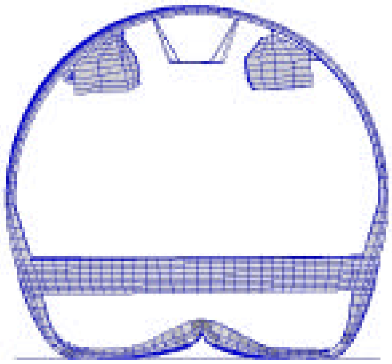


(b) Model deformation.

Figure 26. Photograph of B737 fuselage section with conformable auxiliary fuel tank during impact and corresponding model deformation.

A second drop test was performed at the FAA facility in 2000 of a similar B737 fuselage section. Instead of a conformable auxiliary fuel tank, the cargo hold was filled with 3,000-lb. of luggage. In addition, two different overhead bins were mounted to the fuselage section. The model of the B737 fuselage section with the auxiliary fuel tank was modified to match the second test configuration and pre-test predictions of floor-level and overhead bin acceleration responses were generated. These responses were later correlated with test data and showed remarkable agreement, especially given the number of approximations used in development of the model. A post-test photograph of the B737 fuselage section with luggage and overhead bins and a picture of the deformed model are shown in Figure 27. This work is documented in References 74 and 75.

(a) Post-test photograph.



(b) Model deformation.

Figure 27. Post-test photograph of B737 fuselage section with overhead bins and luggage and corresponding model deformation.

X-38 Crew Rescue Vehicle

In 2000, IDRF personnel were asked by NASA Johnson Space Center to perform landing mishap simulations of the X-38 Crew Rescue Vehicle (CRV) using the nonlinear, explicit transient dynamic finite element code, MSC.Dytran. Three cases were analyzed involving non-deployment of landing gear. The objective of the simulations was to predict the probability of crew injuries during a landing mishap. The MSC.Dytran model was developed from an existing NASTRAN model of the X-38 CRV and crew survivability was estimated using the Dynamic Response Index.[76] A cutaway picture of the model is shown in Figure 28. The analyses showed that the worse case scenario was non-deployment of all landing gear; however, even for this case, the probability of injury was low.[77]

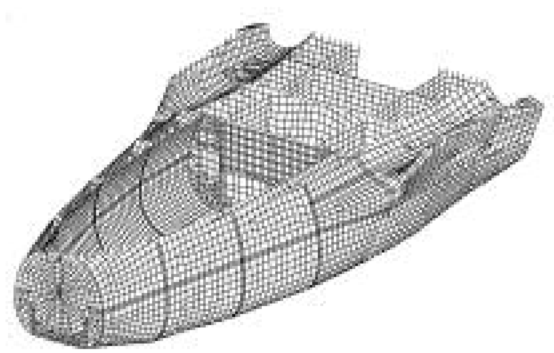


Figure 28. Model of the X-38 CRV.

Conclusions

The Impact Dynamics Research Facility (IDRF) is a 240-ft.-high gantry structure located at NASA Langley Research Center in Hampton, Virginia. The gantry facility was originally built as a lunar landing simulator during the Apollo Program and was used by the Apollo astronauts to practice lunar landings under realistic conditions. In 1972, the facility was converted to a full-scale crash test facility for light aircraft and rotorcraft. Since that time, the IDRF has been used to perform a wide variety of impact tests on full-scale aircraft and structural components in support of the General Aviation (GA) aircraft industry, the US Department of Defense, the rotorcraft industry, and NASA in-house aeronautics and space research programs. Most of the major full-scale crash test programs that were performed at the IDRF since 1974 are described in the paper including highlights of the civil GA aircraft test program, transport aircraft test program, military test programs, space test programs, basic research, and crash modeling and simulation.

Acknowledgements

The authors would like to express their appreciation for the support provided to them in preparing this report by the IDRF staff. Also, we gratefully acknowledge the contributions of Mr. Leroy Burrows, formerly of the US Army AATD, who provided data regarding some of the early military test programs.

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